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Further evidence of the contribution of the ear canal to directional hearing: design of a compensating filter

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4aPPb37. Further evidences of the contribution of the ear canal to directional hearing: design of a compensation filter

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It has been proven, and it is well documented in literature, that the directional response in HRTFs comes largely from the effect of the pinnae. However, few studies have analysed the contribution given by the remaining part of the external ear, particularly the ear canal. This work investigates the directionally dependent response of the modelled ear canal of a dummy head, assuming that the behaviour of the external ear is sufficiently linear to be approximated by an LTI system. In order to extract the ear canal's transfer function, two critical microphone placements (at the eardrum and at the beginning of the cavum conchae) have been used. The system has been evaluated in several positions, along the azimuth plane and at different degrees of elevation. The results point out a non-negligible directional dependence that is well within the normal hearing range; based on these findings, physical models of the ear canal have been analysed and evaluated. We have also considered the practical application to binaural listening, and the colouration originated by the superimposition of the contribution of two ear canals (the listener's and the dummy head's). A compensating FIR filter with arbitrary frequency response is discussed as a possible fix.

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INTRODUCTION

In human directional hearing, Head-Related Transfer Functions (HRTF) are the most important localisation cue. Much of the literature on the topic proves that the directional response in HRTFs comes largely from the pinnae (Middlebrooks (1999); Geronazzo *et al.* (2010).) However, there has been no evidence that the behaviour of the remaining part of the external ear, particularly the ear canal, is not significant to this respect.

In 2009, a study conducted by Hudde and Schmidt (Hudde and Schmidt (2009)) has highlighted some directionally dependent resonances in the ear canal, using a finite-elements physical model of the external ear. Their results show that the sound field at the eardrum is shaped differently when the sound source is placed at different positions along the azimuth plane, particularly at frequencies above 9 kHz, leading to different measured pressures at the eardrum. As a consequence, if these modifications in sound pressure are shown to be non-negligible, it will not be a sensible choice to ignore the ear canal whenever directional hearing is concerned and accuracy in the reproduction of the HRTF is a priority.

One important field of application is dummy-head listening: so far, in many scientific and commercial applications, the ear canal has not been reproduced in the external ear models used in these apparatuses. On the other hand, the inclusion of the ear canal in those devices would negatively influence human listening of the material recorded with a dummy head, in a way that was previously considered negligible: in fact, when listening with headphones is concerned, the source is so close to the ear that pinnae-related resonances are ineffective (Blauert (1996),) but the ear canal still behaves like an open-ended tube. If the dummy head has its own ear canal, the two effect superimpose, giving a distorted representation of the auditory scene.

In this case, it is paramount to filter out one of the two contributions: it is still an open problem whether it is more effective to use the listener's or the dummy head's ear canal as a model to design the compensating filter. A quick and simple implementation, using a FIR filter designed with the windowing method, has been devised for the purpose of this work.

MEASUREMENTS ON A DUMMY HEAD

The first part of the experimental work was about measuring and assessing the directionally dependent contribution of the ear canal found in a typical dummy head, measuring its response at several different positions along the azimuth plane and the elevation plane (ϕ and θ in spherical coordinates).

In order to obtain consistent results, an important theoretical assumption has been made: the dummy head and the room it was enclosed in have been treated as linear time-invariant (LTI) systems. Taking advantage of this assumption, the frequency response of the ear canal could be obtained by measuring the response of the entire system, through a microphone placed at the eardrum, and dividing it by the response of the system *excluding* the ear canal, placing the microphone at the *cavum conchae*.

The system (Fig. 1) has been excited with a 10 seconds long sine-log sweep along the whole audible spectrum (20 Hz - 20 kHz), using a Yamaha MSP3 loudspeaker constantly kept at a distance of 1 m from the dummy head. The source has been oriented in several positions along the elevation (30° above, on axis, 30° below) and the azimuth (on axis, 90° front); a complete cycle of measurements has been done for each position. The results have been recorded at 24 bits - 96 kHz and analysed using a personal computer with a MOTU Traveller sound card and MATLAB.

Fig. 2 shows the ratios between the frequency response of the whole system and the frequency response evaluated at the *cavum conchae*, that is, our estimation of the ear canal's response. It remains very coherent, with the usual strong resonance due to the first resonant mode of the open-ended tube, until 5 kHz; beyond this limit, strong individual differences have been recorded particularly in the 9-12 kHz range and in the 14-16 kHz range, and the data are coherent with Hudde's and Schmidt's findings.

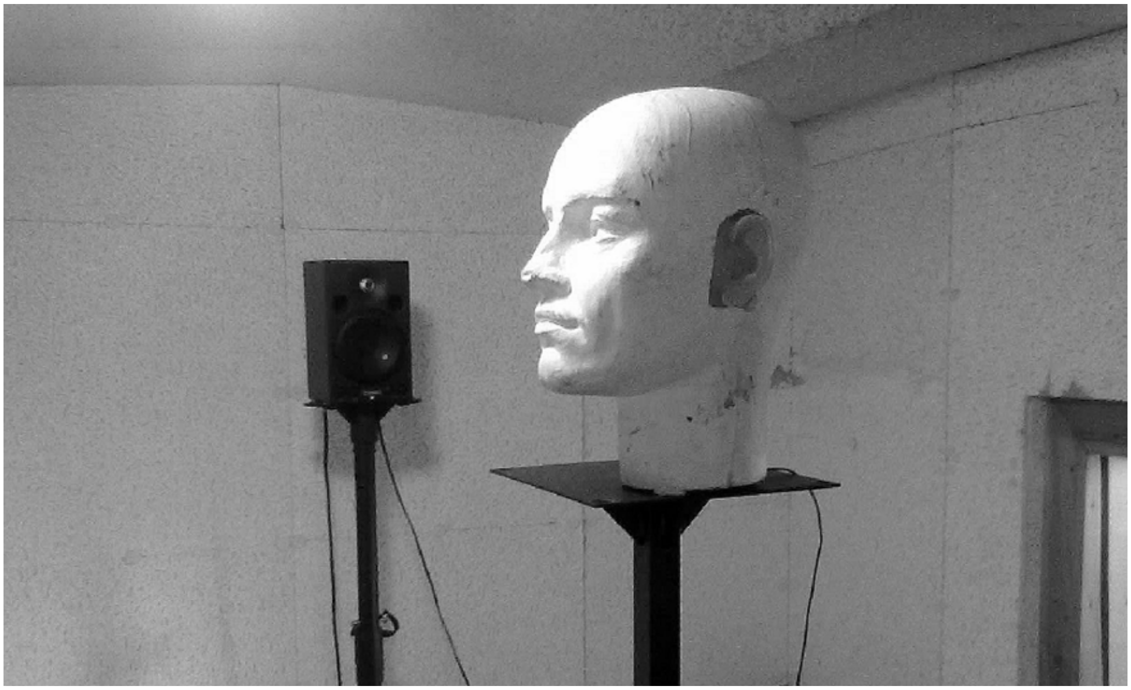

Figure 1: Equipment used for frequency response measurements

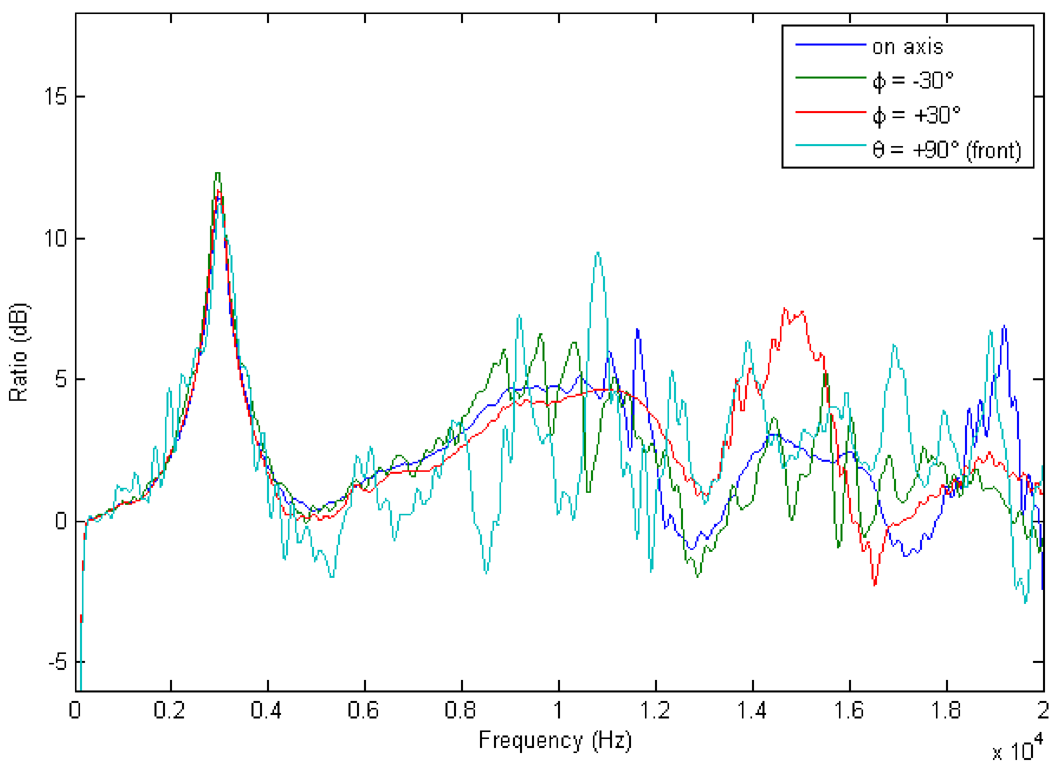

Figure 2: Calculated ear canal frequency responses for different positions along azimuth and elevation coordinates.

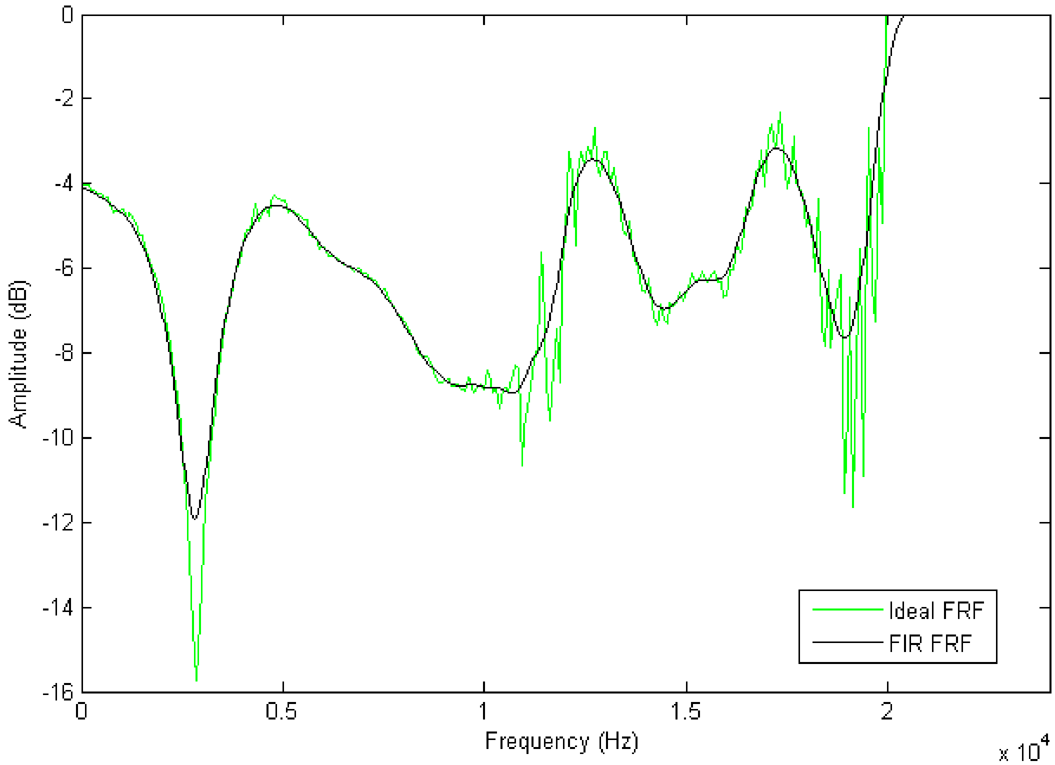

FIGURE 3: Comparison between measured on-axis frequency response of the ear canal and its FIR reproduction

A COMPENSATING FILTER

The use for a compensating filter tuned to the basic non-directional response of the ear canal has been explained above; such a filter should be a nearly perfect inverse reproduction of one of the two ear canals that are present in the listening chain, the listener's or the dummy head's. If the listener's ear canal is chosen, the filter should be made in such a way that it can be easily adapted to reproduce any ear canal, as individual differences in their transfer functions have been proven to be non-negligible (Blauert (1996); Middlebrooks (1999).)

The authors have devised a simple and rudimentary implementation addressing specifically the latter problem: a FIR filter has been designed using the window method. This technique is based upon the inverse Fourier transform of an arbitrary measured frequency response that has been windowed with appropriate functions (Hamming, Chebyshev etc.) in order to control ripples and inaccuracy around critical points. MATLAB's implementation of this method (see MathWorks) has been used to create a 128th-order digital filter with a frequency response specified by amplitude values at 256 frequency points, linearly spaced in the audible spectrum (20 Hz - 20kHz), taken from the measurements made on the dummy head in on-axis positions. A Hamming window has been used to limit inaccuracies. The result of this operation, with a comparison between the ideal Frequency Response Function (FRF) and the actual transfer function of the filter, can be seen in Fig. 3.

In order to assess the effectiveness of such a filter in the preservation and enhancement of the localisation cues, a thorough binaural testing should be made, consisting in several blind psychoacoustic tests with binaural listening, as described in current literature (Blauert (1996).) So far, the solution devised by the authors has not yet been tested under adequate conditions; this problem is still open and it requires further research.

CONCLUSIONS

The experimental work on the dummy head confirms what has been found by Hudde *et al.*(Hudde and Schmidt (2009),) in terms of a series of approximated frequency response functions: the ear canal's response is directionally dependent, although several sources treat it as an open-ended tube with constant section and fixed high-impedance termination (the eardrum). This model, however, has been proven inaccurate for frequencies higher than 2 kHz (Blauert (1996).) A more detailed approximation represents the ear canal as a sequence of concentric segments with varying section, but still it has no directionally dependent behaviour. It seems that a rigorous physical model, one that takes the diffraction and absorption phenomena on a complex surface into account, is the only accurate way to represent the ear canal.

Moreover, the entity of those individual differences between the measured FRF suggest that the ear canal's contribution to the Head Related Transfer Functions is not negligible to the human listener; in order to preserve as much of the HRTFs as possible in dummy head listening, experimental work should be done to quantify the improvement when a reproduction of the ear canal, with an appropriate compensating filter, is used.

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